Renewable and Sustainable Energy Reviews 37 (2014) 698–714

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Three fault ride through controllers for wind systems running in isolated micro-grid and Effects of fault type on their performance: A review and comparative study

Rashad M. Kamel

Electrical Engineering Department, Assiut University, Assiut, Egypt

ARTICLE INFO

Article history:
Received 9 December 2013
Received in revised form
5 May 2014
Accepted 17 May 2014
Available online 9 June 2014

Keywords:
Isolated micro-grid
Fault ride through
Fixed speed wind generation system
Super conductor fault current limiter
Modified pitch angle controller
Variable ratio gearbox
Fault type

ABSTRACT

This paper presents survey about Fault Ride Through (FRT) techniques and controllers which employed with all wind generation system types. After presenting a comprehensive FRT survey, paper proposes three Fault Ride Through (FRT) controllers for keeping stability of Fixed Speed Wind Generation (FSWG) system serving in isolated Micro-Grid (MG). The first controller has been implemented by inserting Superconductor Fault Current Limiter (SFCL) in series with wind generator terminals during fault instant. The second proposed FRT controller is modifying the conventional Pitch Angle Controllers (PAC) to can spill and reduce high percentage of extracted mechanical wind power during and subsequent fault occurrence which in turns help stability improvement and restoration. Third FRT technique is performed by adapting the wind turbine gearbox ratio which forces the wind generation system to run far from the maximum power point. The best performance is obtained with the SFCL controller. Superior results are obtained when the three proposed FRT controllers are employed simultaneously. The three developed FRT controllers are simple, reliable and economical attractive.

Effects of fault type on SFCL FRT controller performance are analyzed and investigated in details. The proposed SFCL FRT controller has been tested under single phase, double phase, phase to phase, and three phases to ground faults. Results display that the three phases to ground fault is the most severe type on SFCL FRT performance from stability point of view. On the other hand, double phase to ground fault is the most severe one from fluctuations and oscillations points of view. Parameters of the SFCL must be adjusted based on the three phases to ground fault. If the SFCL FRT controller is designed to can deal with three phases fault, it sure can deal with the other fault types successfully.

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E-mail address: r_m_kamel@yahoo.com

http://dx.doi.org/10.1016/j.rser.2014.05.065

1. Introduction

A MG consists of a cluster of micro sources, energy storage device (e.g. flywheel, battery, ultra capacitor,……) and loads, operating as a single controllable system. The architecture of the MG is formed to be radial with a number of feeders. The MG often provides both electricity and heat to the local area [1–5]. In fact, connecting small generation units (micro sources) with power rating less than few tens of kilo Watts to low voltage networks potentially increase the reliability for end users. This brings additional benefits to the globally system operation and planning regarding investment reduction for future grid reinforcement and expansion [6]. MG usually contains several renewable energy micro sources like photovoltaic and wind generation system. During the standalone mode, MG feeds its loads locally. In this case, a small storage micro source (flywheel, battery or ultra capacitor) is used as a slack bus to balance load and generation power inside the MG. If any micro source inside the MG failed or became unstable, the slack bus (supplied from small storage micro sources) cannot compensate the missing power and the MG will transfer to black out unless activation of load shedding strategy.

New micro sources (e.g. several kinds of micro gas turbine, fuel cell, photovoltaic panel, and some types of wind turbines) installed in MG are not suitable for supplying energy to MG directly [7]. They must be interfaced with MG through inverters. Thus using of power electronic interfacing in MG led to a series of challenges in designing and operating the MG [7,8]. Maintaining MG stability and power quality during the islanding mode requires more sophisticated inverter control strategies and Fault Ride Through (FRT) control (to overcome fault conditions).

1.1. General overview of FRT and MG dynamic performance

Several literatures discussed the dynamic performance of MG especially during standalone mode. Our previous research developed a dynamic model for every component in MG. References [9–10] presented detailed models for all MG components. Also, standalone performance of each MG component was tested. A literature review on integration of distributed energy resources in the perspective of control, protection and stability of MG has been discussed in [11]. Reference [12] presented a detailed analysis

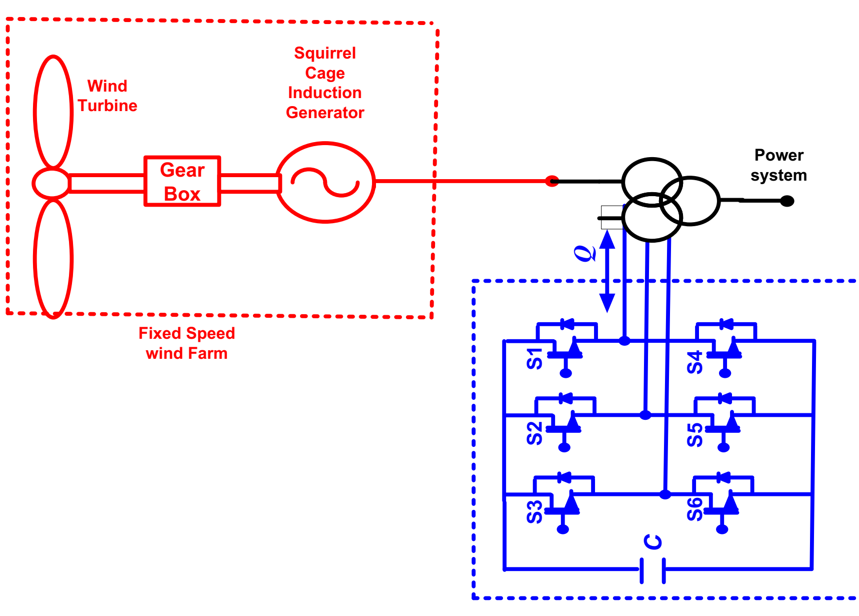

Fig. 1. STATCOM circuit configurations and connection with FSWGs.

of MG stability during islanding mode under different load conditions. Reference [13] presented a comprehensive review of primary control strategies for islanded microgrids with power-electronic interfaces. Reference [14] presented a review of coordination strategies and protection schemes for MGs. Comprehensive review about topologies and control strategies of multi-functional grid-connected inverters for power quality enhancement is presented in reference [15]. In [16–19], authors proposed and developed several techniques and controllers for MG dynamic response enhancement and energy management during both grid connected and islanded modes. Reference [20] covered the protection issue of MG during utility voltage sag. A comprehensive survey on energy management by strategic deployment of Distributed Energy Resources (DER) are discussed in [21]. Reference [22] presented a review of experimental MGs and test systems. Stored energy in PMSG for FRT of wind power system was investigated by [23]. A two degree of freedom internal model control has been integrated and employed for FRT of DFIG wind turbine in [24]. Reference [25] presented algorithm for enhancement of FRT capability of Brushless DFIG driven by wind generation system.

1.2. Wind generation systems technologies

Wind generation systems can be classified mainly as Fixed Speed Wind Generation (FSWG) system [26] and Variable Speed Wind Generation (VSWG) system. The FSWG system type employs a squirrel cage induction generator and this type run at speed slightly higher than the synchronous speed. Because FSWG system runs at nearly constant speed, it has no ability to track the maximum power due to wind speed variations. The VSWG system available in form of Double Fed Induction Generator (DFIG) and Full Converter Wind Generation (FCWG) systems [27,28]. Variable Speed Wind Generation (VSWG) systems are able to adapt its speed and therefore have higher efficiency than FSWGs. Also, existing of power electronics with VSWG system enable it to FRT. Unfortunately, the high cost and low reliability of the electronics that enable variation in speed have discouraged this mode of operation for distributed wind turbines. Alternatively, a Variable Ratio Gearbox (VRG) can be integrated into the FSWGs to facilitate operation with a discrete set of variable speeds that boost efficiency. The VRG concept is based upon mature technology taken from the automotive industry and is characterized by low cost and high reliability. The second reason for developing FRT controllers for FSWGs is the old installed wind generation systems based on FSWGs have average life time about 25 years. Nowadays, it is required from those wind systems to cope with grid code which including FRT capability. Based on this fact, FSWGs must be occupied with FRT controllers to become compatible with grid code during the rest of its life.

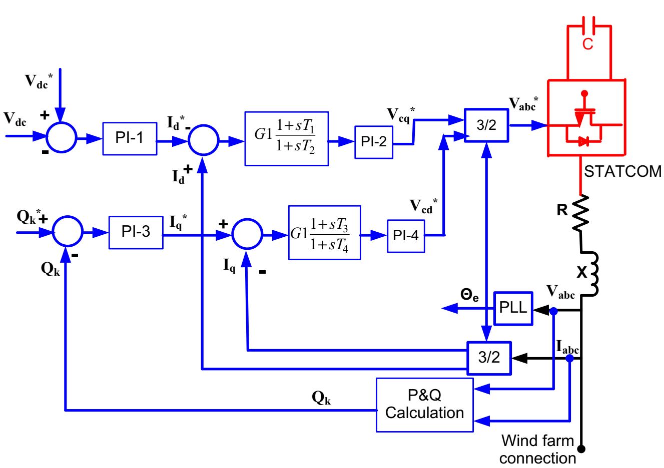

Fig. 2. Control circuit of STATCOM.

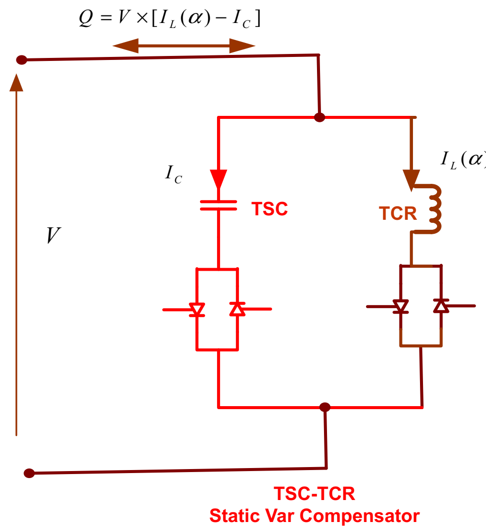

Fig. 3. SVC basic configuration circuit.

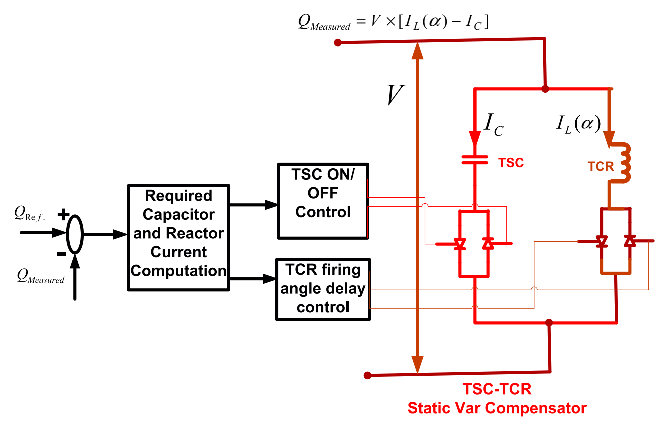

Fig. 4. SVC control model.

1.3. Paper target and organization

All micro sources installed in MG are interfaced with the MG through inverter except Fixed Speed Wind Generation (FSWG) system. This means that, if any fault or high disturbance happens in the MG, a suitable control upon those inverters can keep stability of those micro sources. But FSWGs must be occupied with a certain technique to ride through fault and keep its stability post fault clearing. If there is no FRT controller employed with FSWGs, it will lose its stability and MG loses one micro source and cannot keep its stability during the islanding mode. The main target and duty of this paper is designing and applying three simple and effective controllers to enable FSWGs ride through fault contingency state and maintain its stability. Also the second main target of the present paper is investigating the effects of fault type on the proposed FRT controller performance. In addition, the present paper gives a comprehensive survey about the FRT strategies and controllers which already developed and employed with the wind generation systems and in the literature.

The rest of the paper is organized as follows: Section 2 presents a comprehensive survey about the FRT controller available in the literature which are used with all types of wind generation systems. Section 3 describes the investigated MG. The three

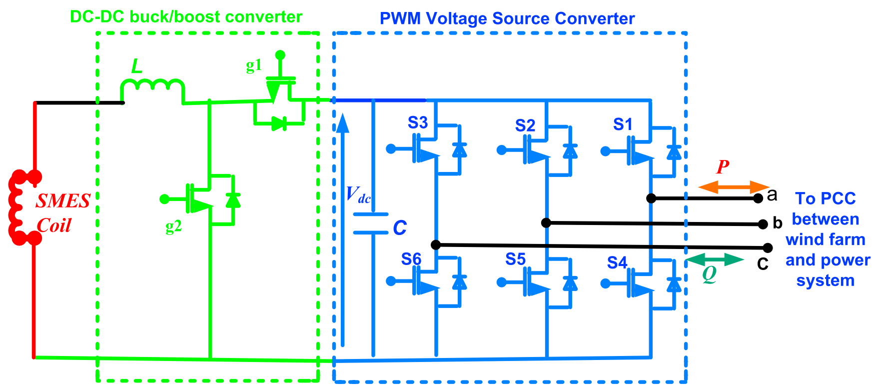

Fig. 5. Basic configuration of SMES system.

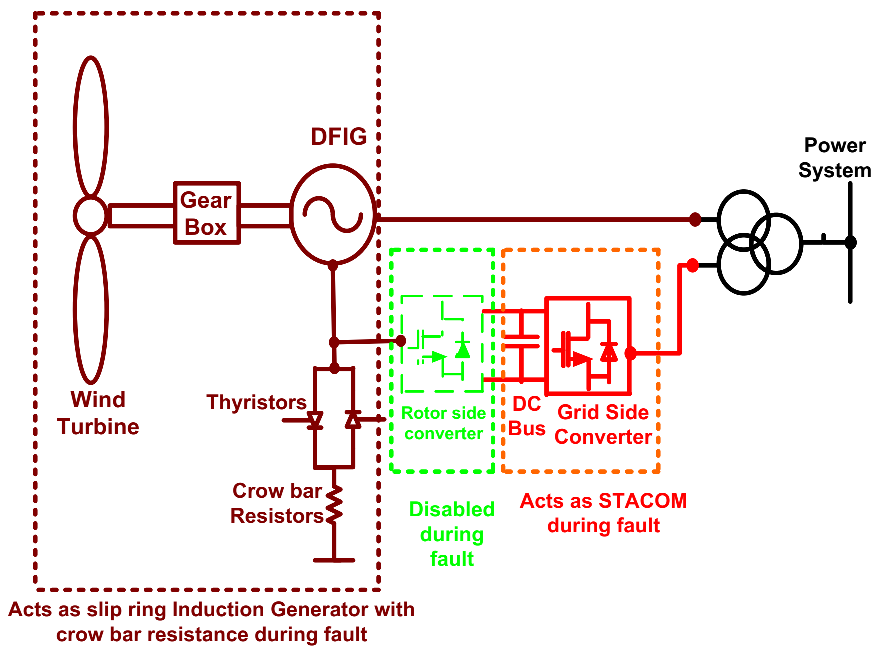

Fig. 6. Configurations of decoupled FRT strategy of DFIG.

proposed FRT controllers are briefly described in Section 4. Results with and without employing the three proposed FRT controllers are presented in Section 5. Effects of fault types on the best developed FRT controller are investigated in detail in Section 6. Conclusions and salient points are summarized in Section 7.

2. Review about employed FRT techniques and controllers with different wind generation system types

In this section, the most important previous developed and proposed wind generation system FRT techniques and controllers will be briefly described and summarized.

2.1. FRT for fixed speed wind generation (FSWG) system using static synchronous compensator (STATCOM)

Static Synchronous Compensator (STATCOM) is proposed to stabilize and fault recovery of the Fixed Speed Wind Generation (FSWG) system in large scale wind farm in Refs. [29–32]. Basic STATCOM configuration is shown in Fig. 1. The STATCOM is connected at the point of common coupling (PCC) between the wind farm and the main grid. During steady state operation, the STATCOM will inject or absorb reactive power to keep the wind farm bus voltage at acceptable value and free from fluctuations. During fault event, the STATCOM will inject its maximum reactive power to help faster voltage recovery and consequently help

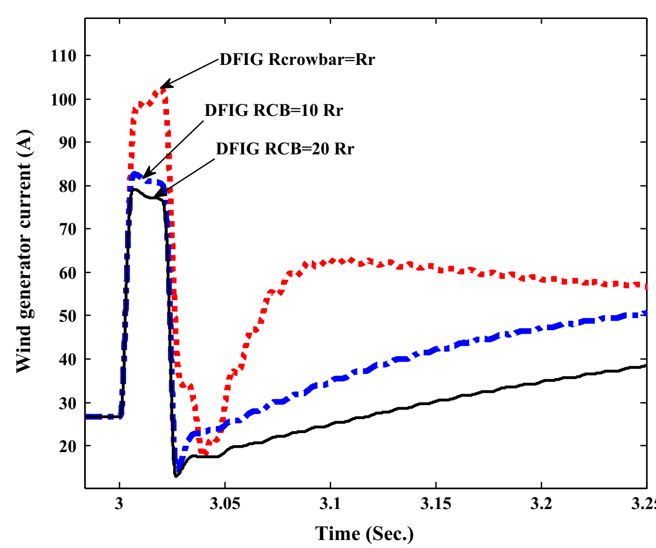

Fig. 7. DFIG fault current with different values of crowbar resistances [60].

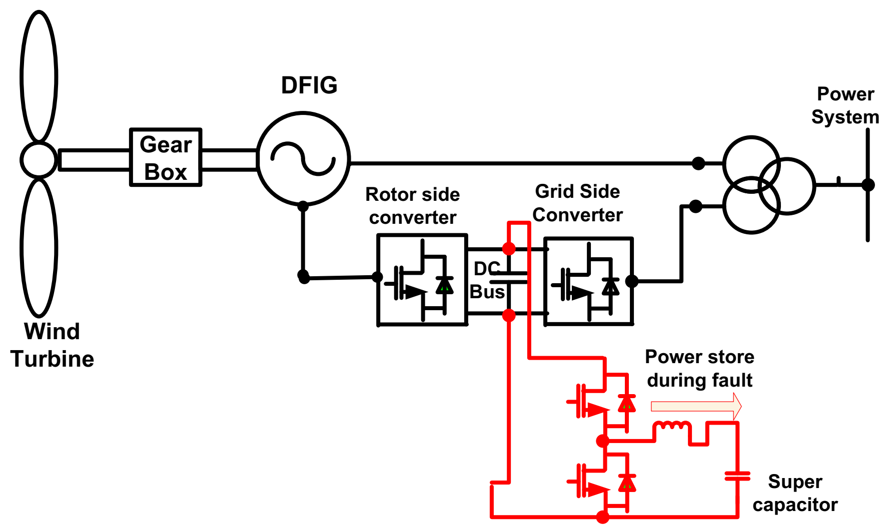

Fig. 8. Using super capacitor as FRT techniques with DFIG.

stability restoration. STATCOM control scheme during fault situation is displayed in Fig. 2. The well-known cascade control scheme is used to control STATCOM as described in details in [17,18,33–39].

2.2. Using Static Var Compensator (SVC) as FRT techniques for FSWGs

Several literatures used Static Var Compensator (SVC) with FSWG system instead of using STATCOM. The SVC has been used as voltage controller (during normal conditions) and as Fault Ride Through controller (during fault event) of FSWG systems [40–45]. Fig. 3 shows the basic circuit configuration of the SVC connected at the terminals of the wind farm. Control scheme which is usually used for SVC control is shown in Fig. 4 and detailed described in Refs. [37,43–45].

2.3. Using superconducting magnetic energy storage (SMES) as FRT technique for FSWGs

Superconducting Magnetic Energy Storage (SMES) is a huge superconductor coil able to store electrical energy in its magnetic field. By using SMES, both active and reactive power can be absorbed or injected from the SMES superconductor coil. Several literatures proposed using of SMES as stabilizing and FRT tool for FSWG system [46–51]. Basic circuit configuration of SMES is shown in Fig. 5. Detailed control algorithms of SMES circuit to stabilize and help FRT process of the FSWGs are available in [46,50,52].

2.4. Using series dynamic braking resistor (SDBR) as FRT strategy for FSWGs

Series Dynamic Braking Resistor (SDBR) is proposed as a tool for FRT and stability restoration of FSWG system in [53]. SDBR insertion with FSWG system terminals limits fault current and keeps terminal voltage at acceptable level. Series resistance insertion displayed a superior performance compared with shunt braking resistance which was used with the conventional power system [54–57]. The SDBR which was developed in [53] is employed with large scale wind farm. In author previous research [58], series dynamic braking resistance was proposed but applied upon small scale wing generation system runs in isolated MG. In the present paper, series dynamic braking resistance based on superconductor fault current limiter is proposed and will be discussed later.

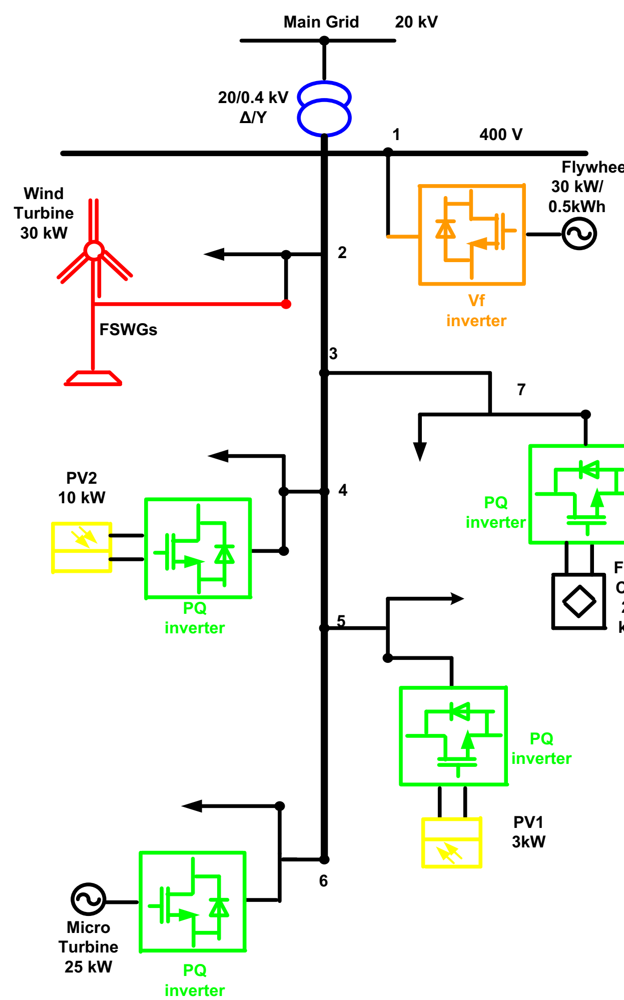

Fig. 9. Architecture of the MG system used for testing the performance of the proposed FRT controllers.

2.5. FRT Techniques for Double Fed Induction Generator (DFIG) system

All previous described FRT methods and controllers in previous Sections (2.1–2.4) are employed with FSWG system. The DFIG variable speed wind generation system employs different FRT

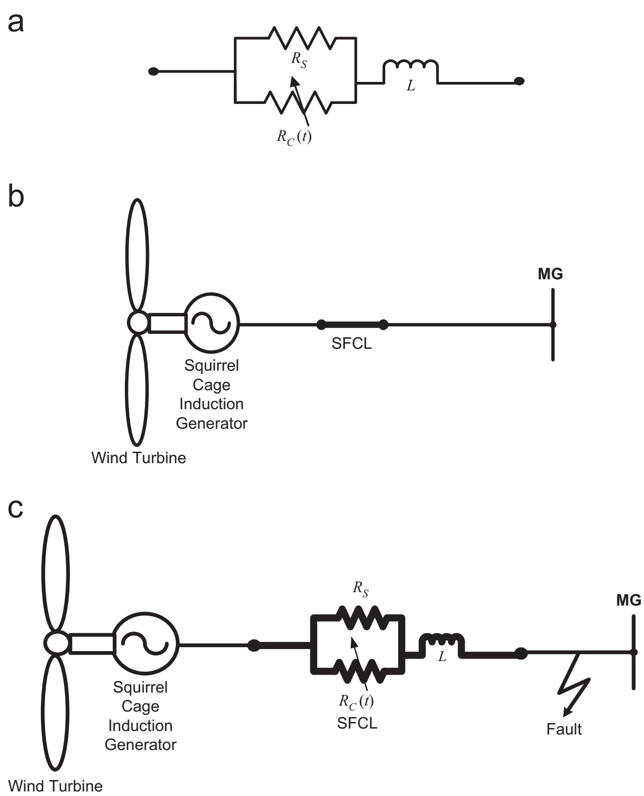

Fig. 10. a: Configuration of SFCL. Fig.10. b: FSWG system arrangement with SFCL under normal conditions. Fig.10. c: FSWGs arrangement with SFCL under fault conditions.

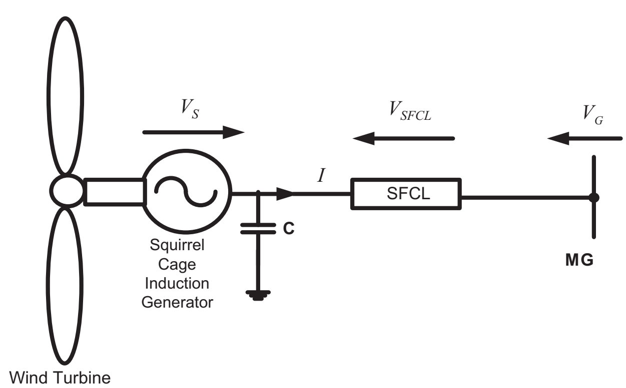

Fig. 11. Wind generation system with SFCL under fault condition.

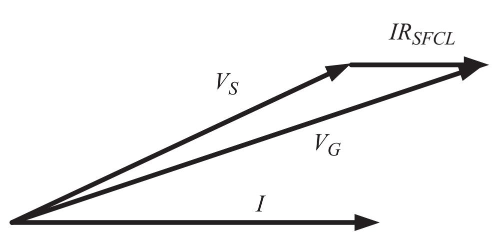

Fig. 12. Phasor diagram shows the effect of SFCL on wind generator stator voltage.

controllers and strategies. Ref. [59] proposes a decoupled FRT strategy for DFIG. The proposed strategy proposes that the DFIG operates as an induction generator with the grid side converter acting as a reactive power source (STATCOM) during a fault condition as shown in Fig. 6. The value of the crowbar resistance has a dominant effect on the fault current and overall fault performance of DFIG as described in detail in author previous research [60]. Fig. 7 shows the fault current of the DFIG installed in MG with three different values of crow bar resistance [60]. Three values of the crowbar resistance are considered. The first case when the crowbar resistance equal to the rotor resistance. The second and third cases are considered when the crowbar resistance equal to ten and twenty times of the rotor resistance, respectively.

In [61], super capacitor energy storage was used for both wind power fluctuation smoothing (during normal condition) and to reinforce the dc bus during transients, thereby enhancing its low-voltage ride through (LVRT) capability. The principle of using super capacitor energy storage for DFIG FRT and wind power smoothing is shown in Fig. 8. Results show that when super capacitor energy storage is sized based upon the LVRT requirement; it can effectively damp short-term power oscillations and fluctuations.

Also, there are several different FRT techniques and strategies applied with DFIG reported in [62–68].

2.6. Full Converter Wind Generation (FCWG) system FRT strategies

For the FCWG system, Reference [69] presented a nonlinear controller design for the Full Converter Wind Generation (FCWG) system. The proposed nonlinear controller ensures that current values remain with design limits even at deeply reduced voltage level (like fault disturbance). The nonlinear control enhances the FCWG FRT capability. In [70], both FRT and wind power smoothing is proposed using STATCOM with Flywheel energy storage system for FCWG system.

3. Architecture of the investigated MG

The MG which used to investigate the performance of the proposed FRT controllers is shown in Fig. 9. As displayed in Fig. 9, all micro sources are interfaced to the MG through power electronic inverters except the FSWGs which is installed at bus #2. FSWG system is connected directly with the MG system. If fault or high disturbance happens in the MG system during the isolated mode, special attention must be given to FSWG system to keep its stability. This is the duty of the present paper. Parameters of MG feeders and MG loads are reported in details through authors previous research [58]. Also, detailed dynamic modeling for all MG components and micro sources are covered in detail in authors previous research [9,10,12,16,18,58].

4. Three proposed fault ride through controllers for FSWG system

In this paper, three FRT techniques are designed and employed to enable FSWGs in fault ride through process and keeping its stability. Consequently keeping the overall stability of the MG running in isolated mode.

4.1. Fault Ride Through (FRT) using Super Conductor Fault Current Limiter (SFCL) (Technique 1)

This technique aims to insert a series resistance with the terminals of the wind generator during the fault period. The resistance insertion topology is based on superconductor technology. The following sections describe the principle and theory of operation of SFCL technique.

4.1.1. Fault Current Limiter (FCL) concept

The Fault Current Limiter (FCL) concept aims to contribute directly in balancing active power during fault moment. It does

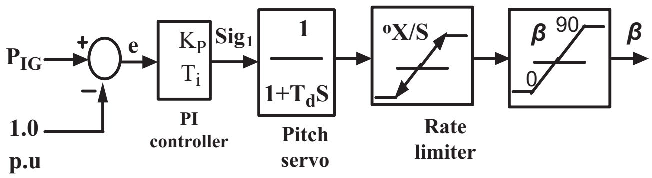

Fig. 13. Conventional pitch angle controller block diagram.

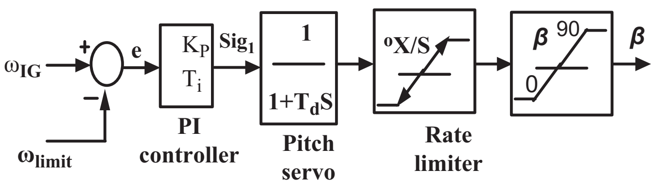

Fig. 14. Modified Pitch Angle Controller (PAC) used for FSWG FRT.

Table 1
Studied cases.

Studied case number	SFCL (Technique 1)	VRG (Technique 2)	PAC (Technique 3)
Case (1)	OFF	OFF	OFF
Case(2)	OFF	OFF	ON
Case (3)	OFF	ON	OFF
Case (4)	OFF	ON	ON
Case (5)	ON	OFF	OFF
Case (6)	ON	OFF	ON
Case (7)	ON	ON	OFF
Case (8)	ON	ON	ON

this by dynamically inserting a resistor in the generator circuit, increasing the voltage at the terminals of the wind generator and thereby mitigating the destabilizing depression of electrical torque and power during the fault period. In this manuscript, Superconductor Fault Current Limiter (SFCL) arrangement has been proposed. The principles and operations of the proposed topology are described as follows:

4.1.1.1. Superconductor Fault Current Limiter (SFCL) Configurations. The SFCL prevents the short circuit current from increasing its magnitude by its rapid current limit ability. The simple structure of SFCL unit is shown in Fig. 10a. The unit consists of the stabilizer resistance R_S, the super conductor resistance $R_C(t)$ which is connected in parallel with R_S, and the coil inductance L. The value of stabilizer resistance (R_S) is not equal zero. However, the overall resistance of the parallel connection equal zero because the value of the super conductor resistance (R_C) is zero in steady state condition. The value of $R_C(t)$ becomes non-zero time-varying parameters during fault depending on its characteristics [71]. The value of L is determined by the wound coils. This has to be small as possible to reduce AC loss under the normal conditions [72]. Then, the associated equation for R_{SFCL} is expressed by Eq. (1) to describe its characteristics.

$$R_{SFCL}(t) = R_m(1-\exp(-t/T_{SC})) \tag{1}$$

where R_m is the maximum resistance of super conducing coil during the normal state when the SFCL is connected to the MG, and T_{SC} is the time constant to transit from the superconducting state to the normal state (usually in range 1 ms).

4.1.1.2. Schematic circuit of FSWGs with SFCL. The general schematic arrangement of FSWG system with Superconductor Fault Current Limiter (SFCL) is displayed in Fig. 10b and c. The SFCL located between the wind generation system and the MG. During normal conditions, the SFCL acts as a short circuit (zero equivalent resistance) and has no influence (Fig. 10b). If the current exceeds than certain threshold (during fault), the SFCL will transit from the superconductor state (zero equivalent resistance) to normal state (has certain resistance) as shown in Fig. 10c.

4.1.2. Phasor diagram and mathematical models of SFCL

Fig. 11 shows the conceptual of the wind generator circuit under fault conditions when the SFCL is inserted. The effect of SFCL insertion on the wind generator stator voltage is illustrated by the phasor diagram shown in Fig. 12 (lagging power factor). It can be seen from the phasor diagram that the generator stator voltage (V_S) increased in magnitude by the voltage IR_{SFCL} (voltage across SFCL resistance).

Since induction generator electromagnetic torque is proportional to the square of its stator voltage, it can be inferred that the presence of SFCL will increase the electrical power extracted from wind generation system during fault and therefore reduce its speed acceleration. This effect would improve the post-fault recovery of a wind generation system. Detailed mathematical analysis and algorithm of how the SFCL help in FRT can be found in author previous research [58].

4.2. Fault Ride Through (FRT) using Variable Ratio Gearbox (VRG) (Technique 2)

The previous FRT controller (SFCL) tried to keep FSWGs stability by keeping stator voltage as high as possible during and post fault. Maintaining voltage at high level enhances the value of electromagnetic power and improves the wind generation system stability. However, the mechanical power is constant. If the mechanical power which drives the wind generator is reduced, the wind generation system stability gets more improvement. The captured mechanical wind power can be reduced and damped by changing the wind turbine speed. The Variable Ratio Gearbox (VRG) technique is employed to verify this task.

4.2.1. Variable Ratio Gearbox (VRG) concept

The mechanical extracted power of wind turbine can be calculated by the following equation [73]:

$$P_m = C_P(\lambda,\beta)\frac{\rho A}{2}V_W^3 \tag{2}$$

As indicated in Eq. (2), the extracted mechanical wind power highly depends on the tip speed ratio (λ). The tip speed ratio is defined as

$$\lambda = \frac{\omega_{tur} r}{V_W} \tag{3}$$

where: $\omega_{tur.}$ is the wind turbine radial speed (rad/s), and $r$is the radius of wind turbine rotor (m).

The percentage captured mechanical power by the wind turbine from the blowing wind power (i.e. C_p) is highly depended on tip speed ratio (λ). Based on Eq. (3), the tip speed ratio (λ) can be controlled by controlling the wind turbine speed. For researchers who concern with operating wind turbine at Maximum Power Point (MPP), they try to operate the wind turbine at ω_{tur} corresponds to λ_{opt} which verify the maximum extracted power.

Gear Ratio (GR) is defined as [74]

$$GR = \frac{\omega_{gen}}{\omega_{tur}} \tag{4}$$

where,ω_{gen} is the wind generator speed (rad/s).

As it is known from machine principles, the squirrel cage induction generator which is used with FSWG is run at nearly constant speed (slightly higher than its synchronous speed). This means that $\omega_{gen}$is constant. From Eq. (4), $\omega_{tur}$is given by the

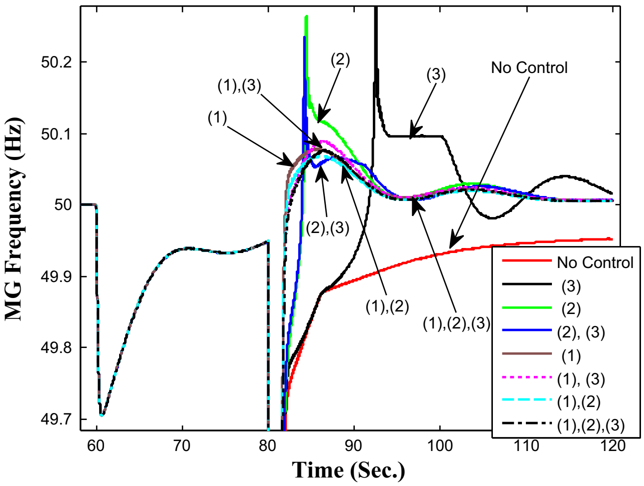

Fig. 15. MG frequency with the eight studied cases.

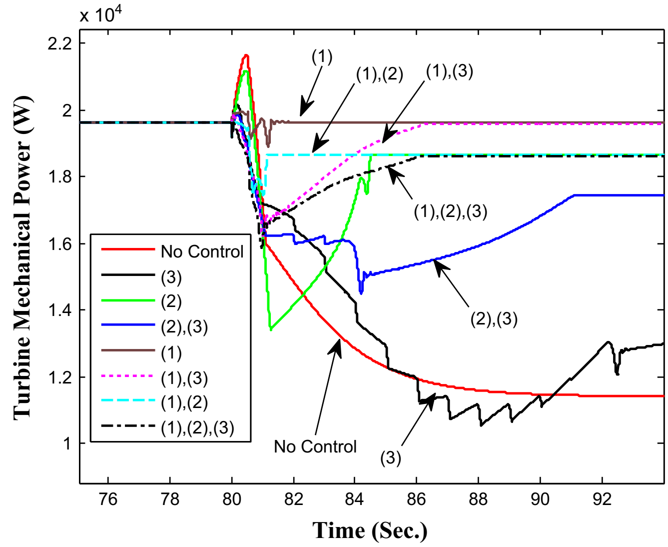

Fig. 18. Wind turbine mechanical extracted power.

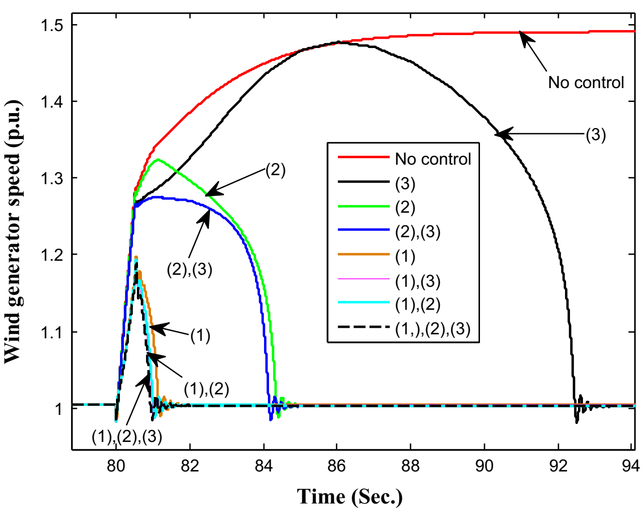

Fig. 16. Speed of wind generator under the eight studied cases.

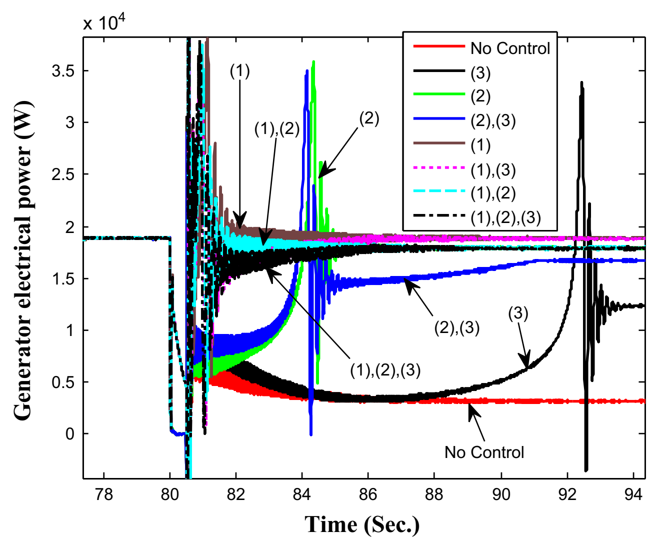

Fig. 19. Wind generator electrical generated active power.

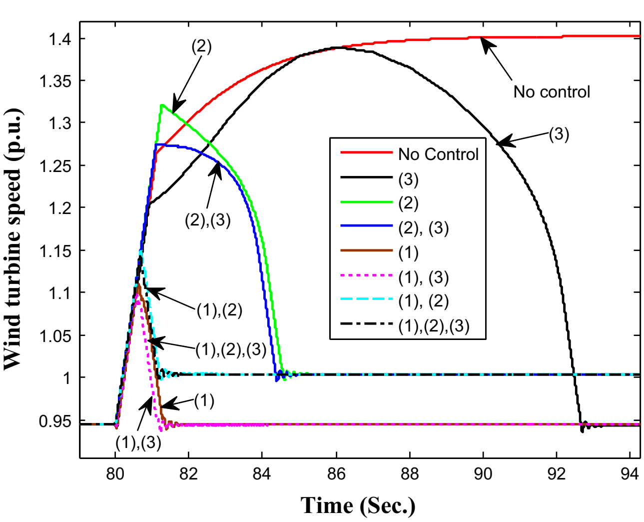

Fig. 17. Wind turbine speed with the eight studied cases.

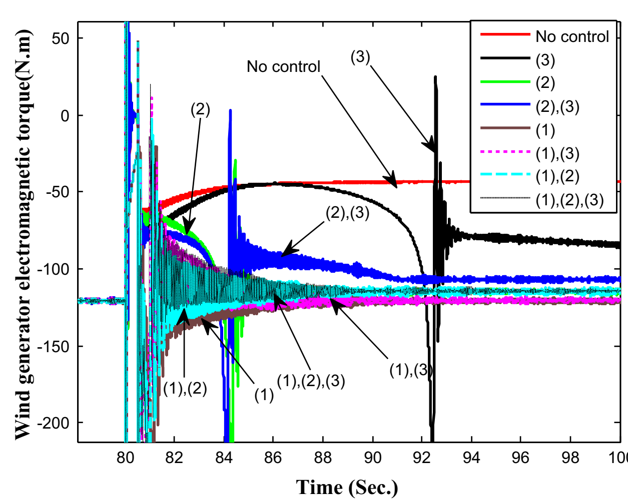

Fig. 20. Wind generator electromagnetic torque.

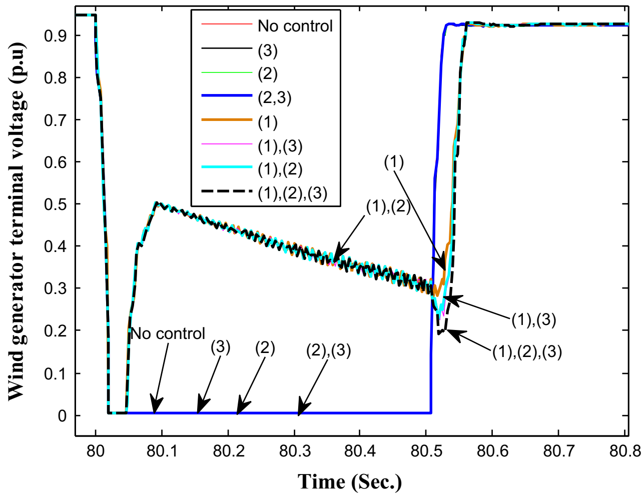

Fig. 21. Wind generator terminal voltage.

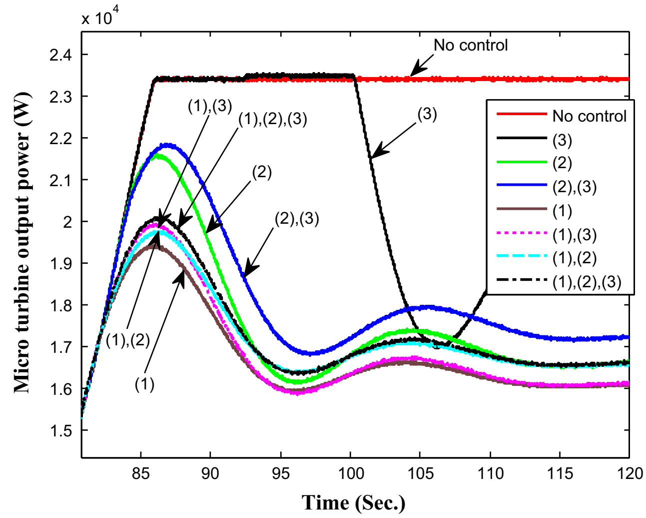

Fig. 23. Active power generated by micro turbine (bus#6).

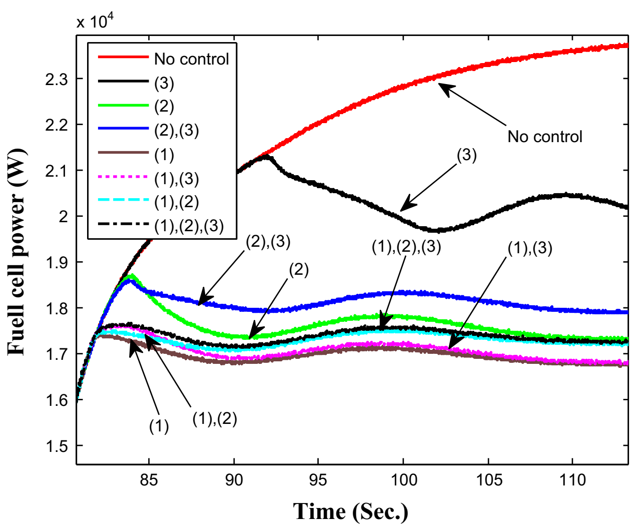

Fig. 22. Active power produced by fuel cell (bus#7).

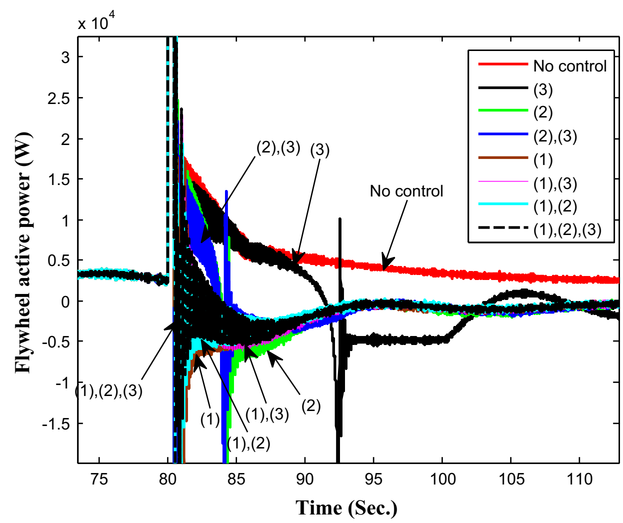

Fig. 24. Active power produced by flywheel (bus#1).

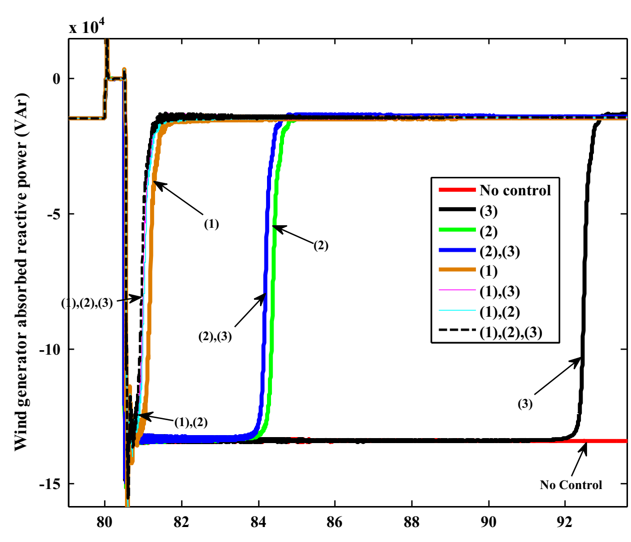

Fig. 25. Wind generator absorbed reactive power.

following equation:

$$\omega_{tur} = \frac{\omega_{gen}}{GR} = \frac{cons}{GR} \tag{5}$$

From Eq. (5), changing ω_{tur} (to get max. power during normal operation) can be obtained only by changingGR

Including Eq. (5) in (3), we obtain

$$\lambda = \frac{\omega_{gen} * r}{GR * V_W} \tag{6}$$

As shown from Eq. (6), the tip speed ratio depends on the value ofGR. Consequently, the power coefficient $C_P(\lambda, \beta)$ and the wind turbine mechanical captured power will also depend on the value of the gear ratio (GR). More details about the mathematical and principle of operation of the VRG and how it can be employed and activated with the FSWG system FRT process can be found in author previous research [75].

4.3. Fault Ride Through (FRT) using modified pitch angle control (PAC)(Technique 3)

The previous VRG FRT technique tried to keep FSWGs stability by reducing the extracted mechanical wind power by modifying the GR to force the wind turbine running far from the maximum

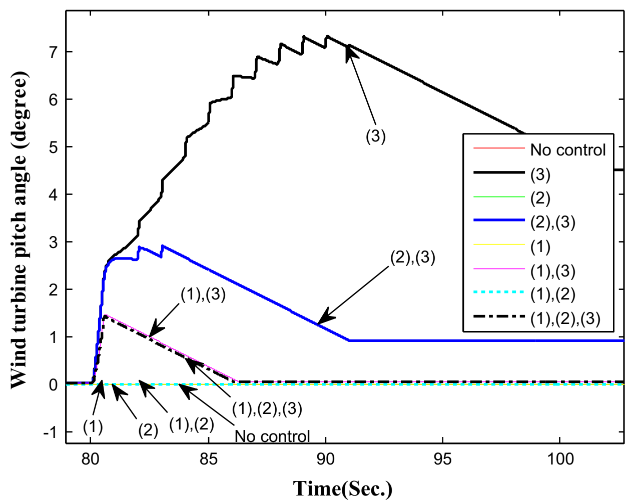

Fig. 26. Wind turbine blade pitch angle.

power point. The mechanical power can also be reduced and damped (during fault) by increasing the blade pitch angle. The pitch angle technique increases the wind turbine blade pitch angle with maximum rate to spill the maximum possible amount of wind turbine extracted mechanical power and help stability restoration.

4.3.1. Mathematical formulation of modified pitch angle control (PAC) FRT technique

As shown in Eq. (2), the extracted mechanical wind power is highly depended on the blade pitch angle. In author previous research [75], detailed analysis of mechanical wind power dependence on the pitch angle can be found. The conventional pitch angle controller which use for power control of the wind turbine during normal conditions is shown in Fig. 13. This controller is used to limit the output power of the wind generator to its rated level when the wind speed exceeds than rated wind speed [17,73].

As shown in Fig. 13, if the generated power exceeds than rated value (1 pu), the pitch angle increase to limit generated wind power to its rated value. The situation is different during fault conditions. During fault situation, the generated power is suddenly drops. If the pitch angle controller remains without any modification, it will not act during fault and cannot contribute in FRT. To overcome this problem, the controller is modified and acts based on the wind generator speed not wind generator power. The generator speed is compared with its upper limit value as shown in Fig. 14. If wind generator speed exceeds than its limit value (during fault situation), the controller will act and increase the blade pitch angle with the maximum possible rate and thereby reduce the extracted mechanical power for helping FRT.

4.4. Employing the three FRT controllers simultaneously

As described before, SFCL controller acts to keep the terminals voltage at considerable value and increase the value of electrical power. On the other hand, both PAC and VRG are employed to reduce the wind turbine captured mechanical power. If the two mechanical FRT controllers (PAC, and VRG) are employed simultaneously, rapid dropping and suppression of wind turbine extracted mechanical power will be achieved. In author previous research [74], the decreasing in mechanical wind power when the PAC and VRG are activated simultaneously is shown in details.

Table 2
Comparison between the performances of the three proposed FRT controllers.

	SFCL	VRG	PAC	Three controllers
Maximum acceleration (% rated speed)	120	133	145	116
Time required to restore system stability (S)	1.5	4.5	13	1.3

5. Results and discussions

To test the effectiveness of the three proposed FRT controllers in keeping the stability of FSWG system, 400 ms three phases to ground fault at the FSWG system terminals (bus #2) is emulated. Eight cases are investigated as described in Table 1.

The following results show the performance of MG system under the eight studied cases. All numbers appeared in the figures represents number of the employed technique as follows: (1) represents SFCL technique employing, (2) represents VRG technique employing and (3) represents PAC technique employing.

- From Figs. 15–26, performance of wind generation system during fault situations under effects of different techniques can be described as follows:
- Before islanding occurrence at t=60 s, the MG was at its steady state and imported about 20 kW from the main grid. The MG frequency was at its nominal value (50 Hz) as shown in Fig. 15. When islanding occurred at t=60 s. The MG lost power imported from the main grid its frequency dropped to about 49.7 Hz (Fig. 15). The MG starts to restore its steady state by increasing active power of controllable micro sources (fuel cell and micro turbine) as shown in Figs. 22 and 23, respectively.
- Twenty seconds from instant of islanding occurrence, three phases to ground fault happened at the terminals of wind generator (bus #2). Fault was cleared 400 ms later. During this period, wind generation system (turbine and generator) accelerated (because Tm > Te) as shown in Figs. 16 and 17.
- During and subsequent fault event, if there is no FRT technique is employed with FSWG system, wind generation system continues in acceleration and became unstable (Figs. 16 and 17). As a result of wind generator acceleration, wind generated electrical active power collapse (Fig. 19). Huge amount of reactive power will be absorbed (due to slip increase of induction generator) as shown in Fig. 25. Final situation is voltage collapse and MG stability deterioration.
- If PAC FRT is employed only with FSWG system, it tries to reduce the mechanical captured wind power (Fig. 18). Due to slow response of PAC (depends on servo pitch long time constant and delay), PAC FRT technique needs nearly 13 s (Figs. 16 and 17) to restore the MG stability. Actually, this response time is very slow and has a bad effect on MG stability and power quality.
- On the other hand, when the VRG controller has been employed, the GR has been changed and reduced the extracted mechanical wind power (Fig. 18). This technique takes nearly 4.5 s to restore wind generation system stability (Figs. 16 and 17).
- The first technique (SFCL) has fast performance in restoring the FSWG system stability when it has been applied upon the FSWG system as shown in Figs. 16 and 17. This is because, SFCL FRT acts upon electrical quantity. SFCL FRT controller require about 1.5 s for completely restoring FSWG system stability.
- If the three proposed FRT controllers are employed simultaneously (case (8)), superior performance is obtained. This is because, the mechanical FRT controllers (PAC and VRG) acts to reduce mechanical power, while the electrical FRT (SFCL)

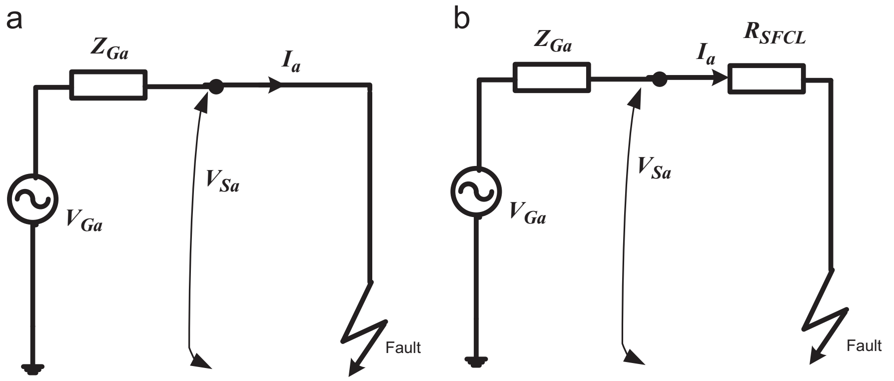

Fig. 27. Three phases symmetrical fault with and without employing SFCL.

technique acts to keep electromagnetic torque at considerable level higher than zero (Fig. 20) by keeping terminal voltage at higher level than zero (Fig. 21) compared with zero value in absence of SFCL.

- Fig. 26 displays the wind turbine blade pitch angle. Value of pitch angle in case 2 (PAC only) is higher than the value of pitch angle in case (8) (all techniques are activated). This is because in case (8), employing the three controllers simultaneously led to small deviation in wind generation system speed (Figs. 16 and 17) compared with high deviation in case (2) (PAC only).
- The dropping in the captured mechanical wind power in case 2, 3 and 8 (Fig. 18) is due to changing the pitch angle and gear ratio. On the other hand, the captured mechanical wind power decreased in case 1 (unstable case) (Fig. 18) due to wind generation system acceleration after fault clearing (Figs. 16 and 17).
- Due to losing the power produced by wind generation system in case 1 (no FRT technique was employed), MG frequency finally settled at nearly 49.95 Hz (Fig. 15) and the controllable micro sources (fuel cell and micro turbine) reached their rated power (Fig. 22, and Fig. 23 with no control). At that moment, controllable micro sources cannot produce any extra power. While in the stable cases (cases 2–8), the wind generation system restored its stability and the MG frequency restored its nominal value (50 Hz). During the stable cases (with employing any or all FRT techniques), fuel cell and micro turbine did not reach their rated power (Figs. 22 and 23 cases 2–8) which means that the MG is far from the blackout mode.
- Fig. 24 displays the active power injected by the flywheel during the eight studied cases. As shown, for the first case (unstable case) the flywheel continues in injecting active power. This means that, after a certain time (depending on the energy capacity of the used flywheel), its storage energy will be totally consumed. At that moment, the MG will transfer to blackout mode unless the load shedding strategy is activated. For the remaining cases (with employing the proposed FRT techniques), the injected flywheel power returned to zero which means that the MG is stable and far from the blackout mode.
- From all previous results, it is found that using SFCL technique leads to minimize the effect of any accompanied employed technique.
- The displayed results indicate that the proposed FRT techniques can improve FSWG system performance and keep MG stability especially if the three techniques are employed simultaneously. The three proposed FRT techniques are simple, cheap which make them applicable for small size wind generation system like the system installed in the MG. Now days, most recently FSWG system are occupied with PAC (for limiting power to the rated value during high wind speed) and VRG (to increase turbine efficiency during normal operation). This means that no hardware or additional equipments are required for implementing PAC and VRG FRT techniques. Only simple control algorithm modification will be included to employ PAC and VRG during fault situation for helping FRT process succession. Also, the three proposed FRT techniques (especially VRG and PAC) are cheaper if they are compared with the STATCOM, SVC, or the SMES which described in Sections 2.1, 2.2 and 2.3.
- In summary, the three proposed FRT controller reduce the wind generation system acceleration and consequently reduce the mechanical stress. This can be seen clearly from the results with and without employing the three FRT controllers (Figs. 16 and 17). As shown in the figures, with employing any one of the proposed techniques the system oscillation is negligible and the acceleration is reduced.

Table 2 summarizes a comparison between the performances of the three proposed FRT controllers.

5.1. Main drawback of the three proposed FRT controllers

From authors point of view the main drawbacks in practical limitations of the proposed FRT techniques are

1. For the SFCL techniques, the circuit of the superconductor coil must be reserved and saved in certain conditions and environment (low temperature) to keep its superconductivity state. If the reserve conditions are different than the designed conditions, the superconducting state may be lost and the SFCL loses its function. At this moment (when the SFCL loses its superconductivity), it will act when the MG system in normal conditions (no fault). With other words, to ensure that the SFCL acts only in fault condition, the conditions which keep its superconductivity must be guaranteed.
2. For mechanical FRT techniques (PAC and VRG), they take long time to restore the system steady state. For example, PAC FRT technique takes 13 s to restore the wind generation system stability (Figs. 16 and 17). From stability and electrical system point of view, 13 s represent very long time and the system may not sustain against this long time. Also, VRG FRT techniques needs 4.5 s (Figs. 16 and 17) to restore system stability and this also represents long time from electrical system stability point of view.
3. Also, amount of acceleration associated with the mechanical FRT techniques (PAC and VRG) is high. For PAC acceleration exceeds than 145% of the rated speed, while for VRG acceleration reached to 133% of the rated speed. Those amounts of accelerations may be not acceptable for many wind generation

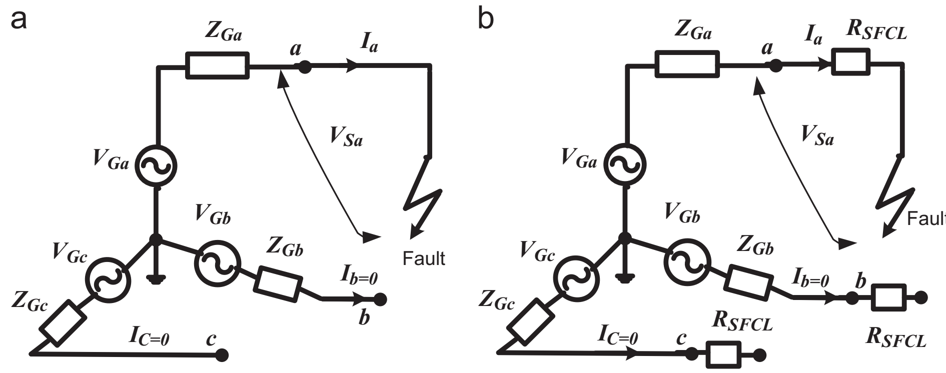

Fig. 28. Single phase to ground fault with and without SFCL.

systems especially the system feeds the critical and sensitive loads like the loads exist in MG system.

4. The already installed wind generation system (old system) which does not includes variable gear box is not able to implement the VRG FRT strategy. In other words, the VRG FRT strategy can only employ with the new wind generation system and it is not possible to include that FRT technique in the old wind system.
5. Also, old wind generation system which use stall control (not provided with pitch control) is not capable for employing the modified PAC FRT controller.
6. The mechanical protection of the wind turbine (locking, braking, Yaw control) must be coordinated with the proposed mechanical FRT controllers (PAC and VRG).
7. The power quality associated with the mechanical FRT techniques (PAC and VRG) may not be acceptable from some sensitive and critical loads point of view.
8. Slow response of both VRG and PAC FRT controllers make them incompatible with the new strict grid codes which are mandatorily applied upon new wind generation systems.
9. For PAC FRT, the high rate change of pitch angle may represent mechanical stress on the servo motor responsible for blade pitch rotate.

6. Effect of different fault types on FRT controller performance

In all previous results, the three FRT controllers are analyzed and tested under the three phases to ground fault only. The question raised here are the fault type has dominant effects on the performance of the FRT controller. In the following sections, the effect of fault type on the performance of SFCL will be analyzed and investigated in detail. The SFCL has been chosen because it gives the best performance and results with FSWG system as shown in Figs. 16 and 17.

6.1. Three phases to ground symmetrical fault

Fig. 27 shows three phases to ground symmetrical fault at the terminals of FSWG system with and without existing the SFCL controller.

Without employing the SFCL with FSWG system (Fig. 27a) the fault current and the wind generator stator terminal voltage are given by [76]

$$I_a = \frac{V_{Ga}}{Z_{Ga}} \tag{7}$$

$$V_{Sa} = 0 \tag{8}$$

where, $Z_{Ga}$is the wind generator phase impedance, V_{Sa} is the wind generator terminal voltage and V_{Ga} is the internal induced voltage of the wind generator.

Because the wind generator stator terminal voltage dropped to zero, its electromagnetic torque will also drop to zero and the machine gain high acceleration without SFCL employing.

On the other hand with employing the SFCL (Fig. 27b), the fault current and the generator stator terminal voltage can be calculated as following:

$$I_a = \frac{V_{Ga}}{Z_{Ga}+R_{SFCL}} \tag{9}$$

$$V_{Sa} = I_a R_{SFCL} \tag{10}$$

As the wind generator stator terminal voltage has a reasonable high value, the electromagnetic torque has an acceptable value and prevents generator speed from high acceleration.

6.2. Single phase to ground fault analysis

Fig. 28 displays the single phase to ground fault disturbance without employing SFCL (Fig. 28a) and with employing SFCL (Fig. 28b).

Without using SFCL the fault current and the wind generator stator terminal voltage can be given by [76]

$$I_a = \frac{3V_{Ga}}{Z_{Ga}^{(+)}+Z_{Ga}^{(-)}+Z_{Ga}^{(0)}} \tag{11}$$

$$V_{Sa} = 0, \qquad T_{ea} = 0 \tag{12}$$

where $Z_{Ga}^{(+)}$ is the positive sequence impedance of the wind generator, $Z_{Ga}^{(-)}$ is the negative sequence impedance of the wind generator ($Z_{Ga}^{(+)}=Z_{Ga}^{(-)}$). $Z_{Ga}^{(0)}$ is the zero sequence impedance of the wind generator. T_{ea} is the electromagnetic torque of wind generator phase a.

For star connected winding induction machine with an earthed neutral, the zero sequence reactance is finite and being smaller than the motor starting reactance and does not vary with time [77]. The zero sequence resistance can be assumed equal to the stator ac resistance [77]. In [78] the zero sequence reactance of asynchronous machine is assumed equal to 20% of the positive sequence value.

For single phase to ground fault at the wind generation system terminals with inserting SFCL resistance (Fig. 28b), the fault current and the stator terminal voltage can be given as

$$I_a = \frac{3V_{Ga}}{Z_{Ga}^{(+)}+Z_{Ga}^{(-)}+Z_{Ga}^{(0)}+3R_{SFCL}} \tag{13}$$

$$V_{Sa} = I_a R_{SFCL} = \frac{3V_{Ga}R_{SFCL}}{Z_{Ga}^{(+)}+Z_{Ga}^{(-)}+Z_{Ga}^{(0)}+3R_{SFCL}} \tag{14}$$

After employing the SFCL, value of fault current has been reduced as indicated in eq. (13), and the machine stator terminal

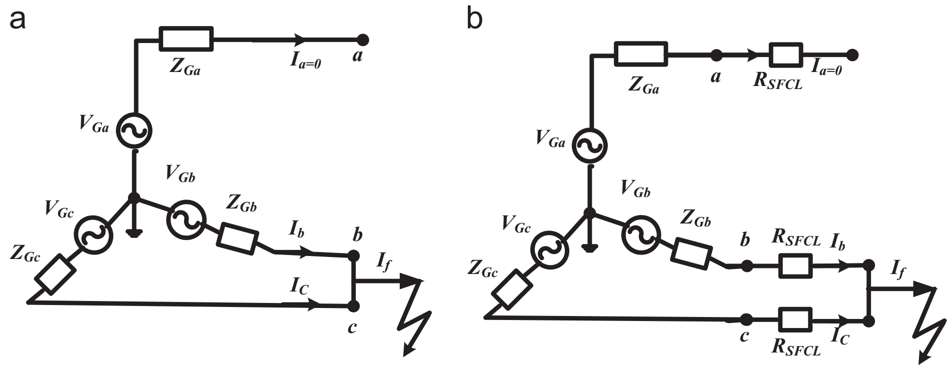

Fig. 29. Double phase to ground fault with and without SFCL.

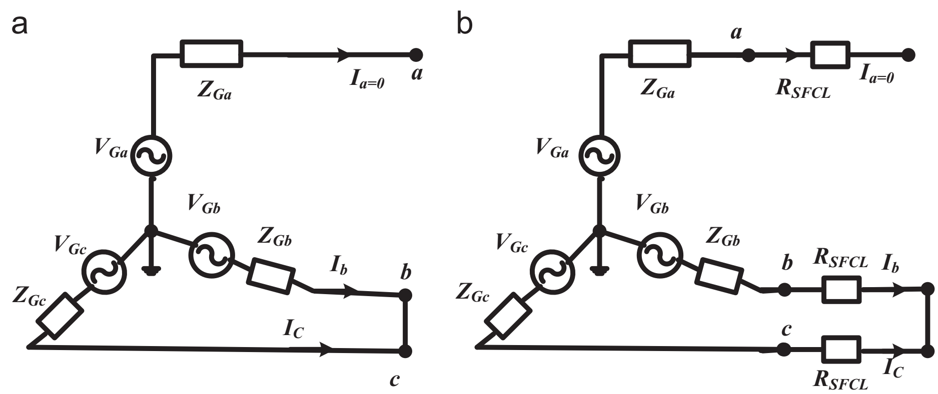

Fig. 30. Phase to phase fault with and without SFCL.

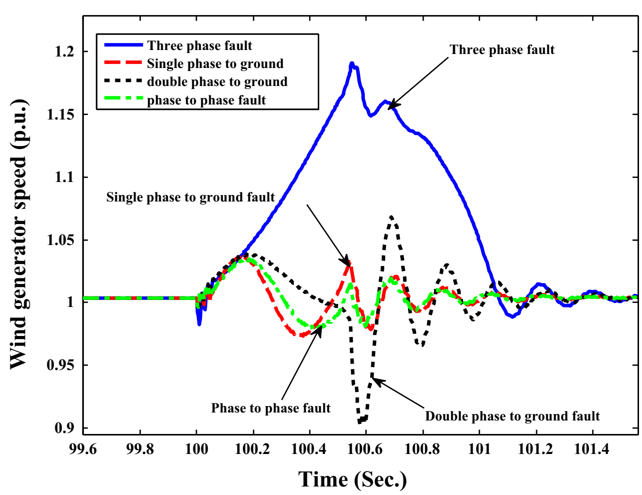

Fig. 31. Speed of wind generator under the four studied cases.

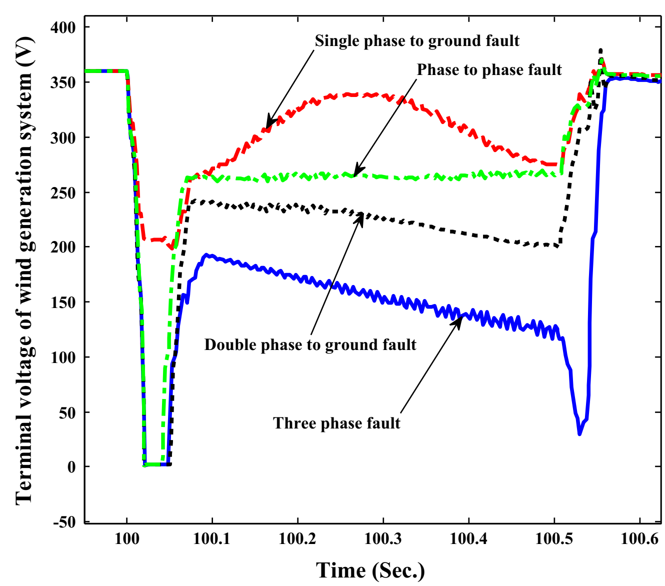

Fig. 32. Voltage at the terminals of wind generator under the four studied cases.

voltage (faulty phase) is increased than zero value. Consequently, the machine electromagnetic torque increases and helps stability restoring.

6.3. Double phases to ground fault analysis

Fig. 29 shows the schematic diagram of wind generation system under double phase to ground fault situation before and after employing SFCL.

Before using SFCL, the faulty phases voltages drop to zero (i.e.$V_b = V_C = 0$). On the other hand with employing SFCL those voltages have certain values higher than zero and can be given as

$$V_b = I_b R_{FCL} \tag{15}$$

$$V_C = I_C R_{FCL}. \tag{16}$$

6.4. Phase to phase fault analysis

Without SFCL, the faulty phases current can be given by [76]

$$I_b = -I_c = -j\sqrt{3}\frac{V_{Gb}}{Z_G^{(+)} + Z_G^{(-)}} \tag{17}$$

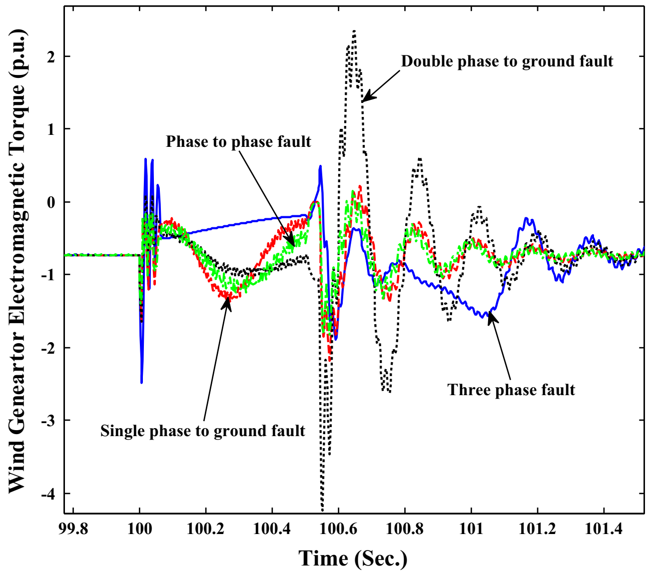

Fig. 33. Electromagnetic torque of wind generator with the four fault types.

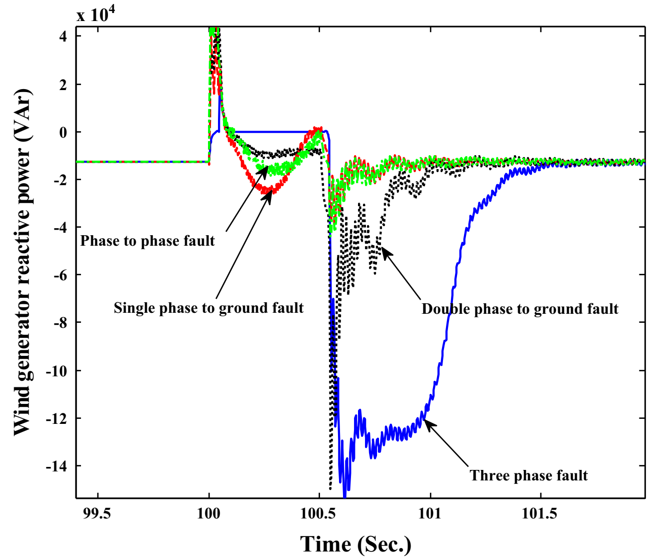

Fig. 35. Reactive power absorbed by wind generator in the four cases.

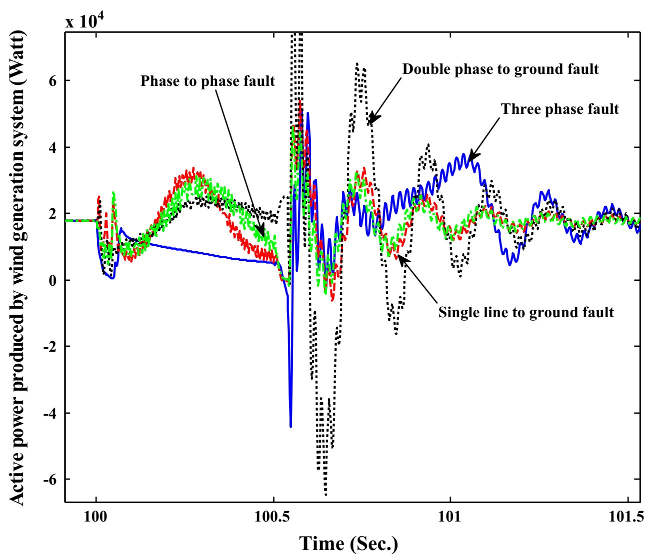

Fig. 34. Active power generated by wind generator under the four studied cases.

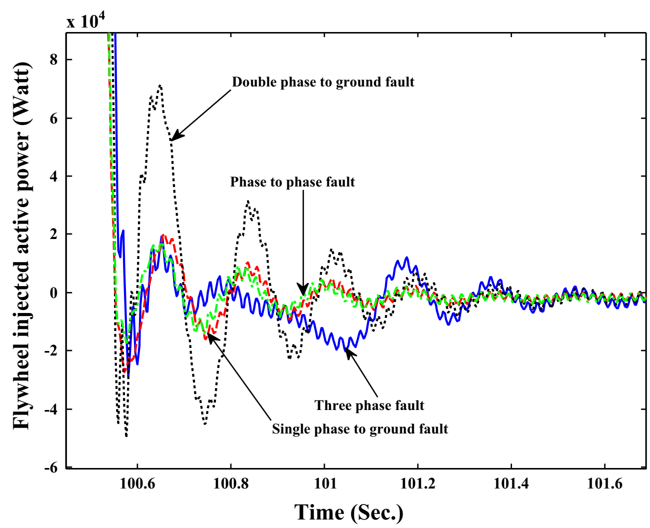

Fig. 36. Active power produced by flywheel in the four studied cases.

With inserting FCL, the faulty phases current can be given by [37]:

$$I_b = -I_c = -j\sqrt{3}\frac{V_{Gb}}{Z_G^{(+)} + Z_G^{(-)} + 2R_{SFCL}} \tag{18}$$

The fault current is reduced with inserting SFCL which in turn help stability improvement.

6.5. Results and discussions

To test and verify the effect of fault type on the proposed SFCL FRT controller performance in keeping and restoring the stability of the FSWG system, four cases are simulated and investigated as follows (in all cases, the wind generation system is equipped with the SFCL FRT controller)

(1) Case 1: 400 ms three phases symmetrical fault at the terminals of wind generation system.
(2) Case 2: 400 ms single phase to ground fault at the terminal of wind generation system.
(3) Case 3: 400 ms double phase to ground fault at the terminals of wind generation system.
(4) Case 4: 400 ms phase to phase fault at the terminals of wind generation system.

In all studied cases, the fault resistance is assumed equal to zero (solid fault). The following results show the performance of MG and the wind generation system under the four studied cases. Fig. 30

Fig. 31 shows wind generation system speed under the four fault types with employing SFCL FRT technique. With inserting the SFCL in series with wind generator terminals the overall system can maintain its stability and restore its steady state after fault clearing. The longest period for stability restoration is about 1.2 s in case of the most severe disturbance (three phases to ground fault). The highest wind generator speed acceleration (20%) is associated with the three phases to ground fault. This is because, during the three phases to ground fault, the generated electromagnetic power dramatically drops (due to voltage dips in the three phases). The mechanical wind power is higher than the electromagnetic power delivered by the wind generation system during fault period. On the other hand, with single phase to

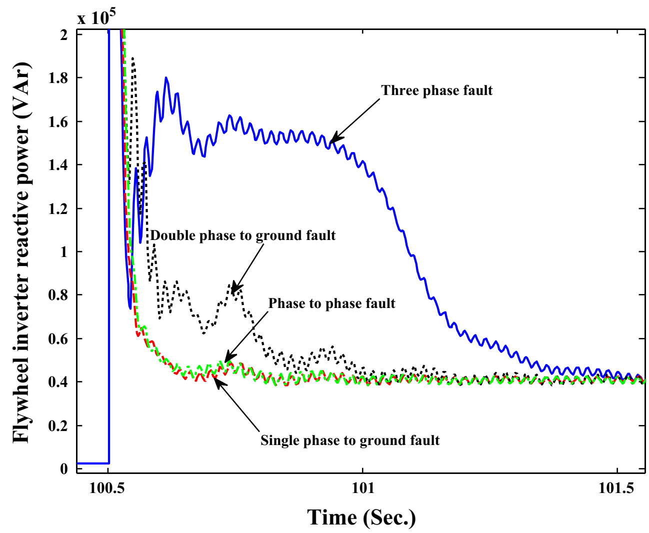

Fig. 37. Reactive power injected by flywheel inverter in the four studied cases.

ground fault, the minimum wind generator speed acceleration (3%) happens during this fault type. This is because, there are two healthy phases still delivers electrical power to the MG. Only the power of one faulty phase drops (due to voltage dips). The same situation is for phase to phase fault type. In this fault type, the faulty phases voltages have small drop and the delivered electromagnetic power still has a reasonable high value which help stability restoration. The most fluctuated case is the case of double phase to ground fault. This is due to high percentage value of negative sequence components on delivered active power which causes high and rapid fluctuation and oscillation. From Fig. 31 one can conclude that:

(1) From acceleration point of view three phases to ground fault is the most severe fault type.
(2) From oscillation and fluctuation point of view double phase to ground fault is the most severe one.
(3) Phase to phase and phase to ground faults have a light effect on wind generation system stability and oscillations.

Fig. 32 displays the wind generation system stator terminal voltage under the four fault types with employing SFCL technique. As shown, inserting SFCL resistance in series with terminals of the wind generation system keeps system voltage at reasonable value higher than zero during fault period. The residual stator voltage value lies between 170 V or 45% (Three phases to ground fault) and 320 V or 85% (single phase to ground fault). Keeping voltage at those higher values is behind keeping and improving the wind generation system stability.

Fig. 33 shows the electromagnetic torque produced by the wind generator under the four fault types. As the electromagnetic torque is proportional with the square of the generator terminal voltage, it has value higher than zero during fault (with SFCL resistance insertion). During fault period, the induced electromagnetic torque for the three phase to ground fault is the lowest ($T_e \propto V_S^2$, V_S=45% for three phase to ground fault). On the other hand, the induced electromagnetic torque for single phase to ground fault nearly reaches the rated value ($T_e \propto V_S^2$, V_S=85% for single phase to ground fault). For double phase to ground fault type, there are very high oscillations in the induced electromagnetic torque due to high unbalanced and consequently high percentage of negative sequence component. In all cases, the electromagnetic torque settles to its steady state value within 1.4 s from fault occurrence instant.

Fig. 34 shows the electrical power delivered by wind generation system. The profile of the generated active power is nearly similar to the electromagnetic torque pattern. Again from oscillation and vibration point of view, the double phase to ground fault represents the most severe fault type. From the amount of drop in the generated active power, three phases fault is the most severe one. Both single phase and phase to phase faults have little effects on wind generation system generated active power and also have little fluctuations.

Reactive power absorbed by wind generation system during the four studied cases is shown in Fig. 35. For three phases to ground fault, wind generation system absorbs a huge amount of reactive power due to high acceleration in generator speed. For single phase to ground and phase to phase faults, amount of absorbed reactive power is small (Fig. 35) due to small acceleration on the machine speed (Fig. 31). For double phase to ground fault, due to high oscillation on the machine speed (Fig. 31), there is high fluctuation on the generated active power (Fig. 34) and also high fluctuation on the absorbed reactive power (Fig. 35).

Because the MG runs in the stand alone mode, the wind generation system active power deficit and fluctuations must be compensated and supplied from the flywheel (storage device). Amount of active power produced by flywheel is shown in Fig. 36. As shown, after fault clearing, the most difficult case for flywheel is the double phase to ground fault. The reason for that is the high fluctuation and oscillation on wind system generated active power (Fig. 34). This oscillation is compensated from the flywheel bus. For the three other fault cases, amount of injected active power is moderate and has low oscillations.

Fig. 37 shows amount of reactive power injected by the flywheel inverter (slack bus). As shown, due to high acceleration in three phase to ground fault case, a huge amount of reactive power must be injected by flywheel inverter to compensate the reactive power absorbed by the wind generation system (Fig. 35). Also, due to high fluctuation of reactive power absorbed by the wind generation system in double phase to ground fault case, the reactive power injected by the flywheel inverter must compensate that oscillated reactive power. For the two other types of fault, amount of injected reactive power by the flywheel inverter is small and has negligible oscillation compared with the three phases and double phase to ground faults cases.

7. Conclusions

This paper gives a comprehensive survey about the FRT techniques and controllers which already have been implemented and proposed with different types of wind generation systems. Also the paper proposed, designed and tested three economical attractive FRT controllers to enable FSWG system from overcoming and ride through fault in isolated MG. the first technique is SFCL which give excellent and fast response when employing with the FSWG system. Results proved that SFCL needs only 1.5 s to restore FSWG system stability. Amount of acceleration with employing SFCL reached to 120% of the rated speed. The second technique is modified pitch angle controller (PAC), which acts to modify wind turbine blade pitch angle to reduce extracted mechanical wind power and consequently suppress the system acceleration during and subsequent fault occurrence. Results indicated that PAC technique needs about 13 s to restore system steady state. Amount of acceleration with PAC reached 145% of the rated speed. This slow response is due to time delay of pitch servo motor used for changing wind turbine blade pitch angle. The third technique is Variable Ratio Gearbox (VRG) which acts to change the wind turbine speed to run far from the maximum power point during fault situation. This action helps in reducing the extracted

mechanical wind power and improves system stability during and subsequent fault occurrence. VRG controller needs about 4.5 s to restore FSWG system stability and the amount of acceleration is 133% of the rated speed. VRG is faster than PAC and slower than SFCL. Superior performance has been achieved when the three proposed FRT techniques are employed simultaneously (need 1.3 s to restore system steady state and amount of acceleration 116% of the rated speed). If there is no FRT controller employed with FSWG system, the wind generation system cannot maintain its stability and the overall MG system will transfer to black out mode. The three proposed FRT controllers are simple, reliable, effective and highly economical attractive.

Effects of fault type on the SFCL FRT performance have been investigated in details. It is found that the three phases to ground fault is the most severe type from wind generation system stability point of view. It accelerated the wind generator with more than 20%.On the other hand, the double phase to ground fault is the most severe one from oscillation and power fluctuations point of view. The single phase to ground and phase to phase fault has small effect on wind generation system stability and results in negligible power fluctuations.

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